Language Acquisition and Cerebral Specialization in 20-Month-Old Infants

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Abstract

■ The purpose of the present study was to examine patterns of neural activity relevant to language processing in 20-month-old infants, and to determine whether or not changes in cerebral organization occur as a function of specific changes in language development. Event-related potentials (ERPs) were recorded as children listened to a series of words whose meaning was understood by the child, words whose meaning the child did not understand, and backward words. The results showed that specific and different ERP components discriminated comprehended words from unknown and from backward words. Distinct lateral and anterior–posterior specializations were apparent in ERP responsiveness to the different types of words. Moreover, the results suggested that increasing language abilities were associated with increasing cerebral specialization for language processing over the temporal and parietal regions of the left hemisphere. ■

INTRODUCTION

During the first 2 years of life the development of speech and language skills is characterized by several rapid and dramatic changes in the ability to comprehend and produce language. This period in infancy is also accompanied by many structural, neurochemical, and neurophysiological changes in brain development. Although attempts have been made to link changes in language development with general changes in anatomical and physiological brain development (Bates, Thal, & Janowsky, 1992; Lenneberg, 1967; Parmelee & Sigman, 1983), this goal has remained elusive, in large part due to the fact that so many aspects of the brain and behavior are changing together. Over the past several years it has become possible to image, noninvasively, the neural events linked to specific aspects of sensory and cognitive processing. The purpose of the present study was to examine patterns of such neural activity relevant to language processing in 20-month-old infants, and to determine which changes in the organization of brain activity occur as a function of specific changes in language acquisition.

Recording of event-related brain potentials, or ERPs, from the scalp is one of few currently available approaches to the study of the neural events associated with information processing in healthy human subjects (see Callaway, Tueting, & Koslow, 1978; Kutas & Hillyard, 1983; Hillyard & Picton, 1987; for reviews). The power of ERPs lies in that they provide information about the sequence, timing, and, in some cases, the location of neural activity elicited by particular stimuli well before subjects produce an overt response. Additionally, this approach bypasses some of the performance-related limitations of behavioral testing with infants and toddlers. Language assessment tasks often require the child to perform some action on request (e.g., point to pictures, answer questions, enact a scene). Performance on these behavioral tasks is influenced by many factors in addition to the child's language abilities, e.g., willingness to cooperate, ability to physically perform the task, and social skills with strangers. Because ERPs do not require an overt response many of these problems can be bypassed. Initially, however, behavioral data are needed to discern which ERP components are linked to language comprehension.

In adults, several ERP components have been linked to specific aspects of cognition and language processing including different parts of speech, the meaning of words, the age at which language was first acquired, and the nature of the language acquired (Ardal, Donald, Meuter, Muldrew, & Luce, 1990; Kutas & Van Petten, 1988; Kutas & Hillyard, 1984; Van Petten & Kutas, 1991; Neville, Mills, & Lawson, 1992; Neville, 1985, 1991a,b).

To the extent that ERPs reveal specific aspects of cerebral organization in the adult, they should be sensitive to changes in brain organization that occur as a function of particular changes in behavioral development in young children as they acquire language. Very few data exist on this point. Rather, a major focus of developmental ERP studies has been to record changes that occur in the morphology, latency, and distribution of ERPs in

Journal of Cognitive Neuroscience 5:3, pp. 317–334

perceptual discrimination tasks as a function of chronological age (e.g., Courchesne, 1983; Karrer & Ackles, 1987; Kurtzberg, 1985; Kurtzberg, Hilpert, Kreuzer, & Vaughn, 1984; Shucard, Shucard, & Thomas, 1987). Furthermore, the majority of ERP studies with infants have recorded responses to visual stimuli from infants 6 months of age and younger (Courchesne, Ganz, & Norcia, 1981; Kurtzberg et al., 1984; Nelson & Salapatek, 1986; Novak, Kurtzberg, Kreuzer, & Vaughn, 1989; Shucard, Shucard, Commings, & Campos, 1981). In one of the few developmental ERP studies on auditory processing of language stimuli, Kurtzberg (1985) characterized a series of positive and negative ERP components elicited to stop-consonant vowel (CV) syllables in infants from 0 to 24 months of age. By 18–24 months of age, ERPs over lateral temporal sites were characterized by two positive components at 150 and 400 msec and two negative components at 275 and 600 msec. In general the latencies of the components decreased with age. The negative component at 600 msec displayed a frontal distribution, and has been linked to the Nc component elicited by visual stimuli (Courchesne et al., 1981). The Nc in infants also displays a frontal distribution and has been elicited to a variety of visual (Courchesne et al., 1981; Karrer & Ackles, 1987) and auditory stimuli (Kurtzberg, 1985; Kurtzberg & Vaughn, 1985).

More recently, Molfese recorded ERPs from 14-month-old (Molfese, 1989) and 16-month-old (Molfese, 1990) infants as they listened to a word whose meaning the child comprehended and a word the child did not appear to know. The data from both studies suggested that ERPs to these stimuli indexed differences in neural activity associated with language comprehension. Moreover, the distribution of the differential responsiveness to comprehended and unknown words varied both as a function of latency (over the ERP epoch), and chronological age. Additionally, for the 16-month-olds, the distribution of the difference between the comprehended and unknown words was different for girls and boys. For girls, responsiveness to the different types of words was lateralized to the left hemisphere, while for boys the difference was bilateral. Several studies have reported sex differences in the rates of language acquisition, with girls usually demonstrating better performance than boys (e.g., Nelson 1973, 1975; Ramer, 1976). It may be that the more lateralized responsiveness displayed by the girls in Molfese's (1990) study reflected a higher level of competency with language. Unfortunately, it is not possible to discern which effects may be due to sex and which to levels of language ability because there was no information given on the language abilities of the subjects in either study (Molfese, 1989, 1990).

The role of language competency in the organization of neural systems subserving language processing has been explored in several studies of adults, both of normal hearing and congenitally deaf adults (Neville, 1991a,b; Neville, Kutas, & Schmidt, 1982a,b; Neville, Mills & Lawson, 1992). The results from these studies suggest that the specialized role of the left hemisphere for a given language arises pari passu with increasing knowledge of a language (i.e., English or American Sign Language, ASL). A similar pattern has also been demonstrated with bilingual adults (Weber-Fox & Neville, 1992), and in language-impaired children (Neville, Holcomb, Coffey, & Tallal, 1989; Neville, Coffey, Holcomb, & Tallal, 1993).

In the present study we tested the hypothesis that during the course of primary language acquisition the development of cerebral specializations for language is linked to changes in specific levels of language abilities. The approach taken here was to study a group of children who were the same chronological age but had attained different language milestones. This type of design permitted any differences in brain organization to be attributed to language knowledge rather than to general maturational changes. We chose to study 20-month-old infants because this age is a pivotal time in language development and is accompanied by a substantial degree of normal variability in language abilities. This period in development is typically associated with a burst in vocabulary size for both comprehension and production, and this period also marks the onset of word combinations (e.g., Bates, Bretherton, & Snyder, 1988; Goldfield & Reznick, 1990). One of the best indices of general language abilities at 20 months is the size of a child's productive vocabulary (Bates et al., 1988; Bretherton, McNew, Snyder, & Bates 1983).

In the present study we used the size of the child's productive vocabulary to assign children into two groups varying in language abilities. ERPs were recorded as the children listened to words they comprehended, words they did not comprehend, and backward words. We predicted that specific ERP components would be sensitive to language comprehension and that increasing levels of language abilities would be associated with increased specializations of neural systems subserving language processing.

RESULTS

Behavioral Data

A summary of the children's performance on tests of language production and language comprehension is shown in Table 1. A full description of each of the measures is provided in the Methods section. The data were analyzed separately for sex and family history for left handedness (FHLH) in one-way ANOVAs (group × score). Family history for left handedness was determined by parental report of sinistrality in the immediate family. Separate ANOVAs were conducted for the scores on two measures of language production abilities and two measures of language comprehension abilities.

Table 1. Behavioral Test Scores (Means and Standard Errors) as a Function of Sex, Family History for Left-Handedness, and Production Group

	Language production and comprehension			
	ELI	*Vocab checklist*		*Comp Books*
	No. words prod	*No. prod*	*No. comp*	*(% correct)*
All 24 subjects	184 (31.9)	45 (5.7)	77 (3.7)	75 (3.7)
Range	(33–531)	(11–100)	(42–100)	(34–93)
Girls (16)	221 (42.1)	52 (7.1)	81 (4.7)	76 (4.8)
		*		
Boys (8)	110 (28.5)	28 (6.1)	69 (5.2)	74 (5.6)
FH+ left (11)	178 (50.9)	39 (9.3)	73 (6.9)	73 (6.5)
No left (13)	189 (40.1)	50 (6.9)	81 (3.3)	77 (4.5)
High producers (11)	310 (42.6)	66 (6.9)	84 (4.8)	83 (3.4)
	†	**		*
Low producers (13)	77 (9.4)	25 (3.3)	71 (5.1)	66 (5.7)

*$p<0.05$.
**$p<0.01$.
†Groups are different by definition.

Language Production

Two parental report measures, the Early Language Inventory (ELI) and the vocabulary checklist rating scale, provided measures of productive vocabulary for each of the children. On the ELI, girls tended to produce more words than boys, however the difference only approached significance, $p=0.09$ (see Table 1). On the vocabulary checklist rating scale, the number of words parents indicated they were "very sure" their child said and used in a variety of appropriate contexts, was also higher for girls than boys [$F(1,21)=4.57, p=0.045$]. There were no significant differences in the number of words produced between children with and without a FHLH on either measure of language production.

Language Comprehension

The vocabulary checklist rating scale and the comprehension book, a picture pointing task, were used for measures of language comprehension. There were no significant differences on these measures between boys and girls or between children with and without a family history of left handedness on either measure (see Fig. 1).

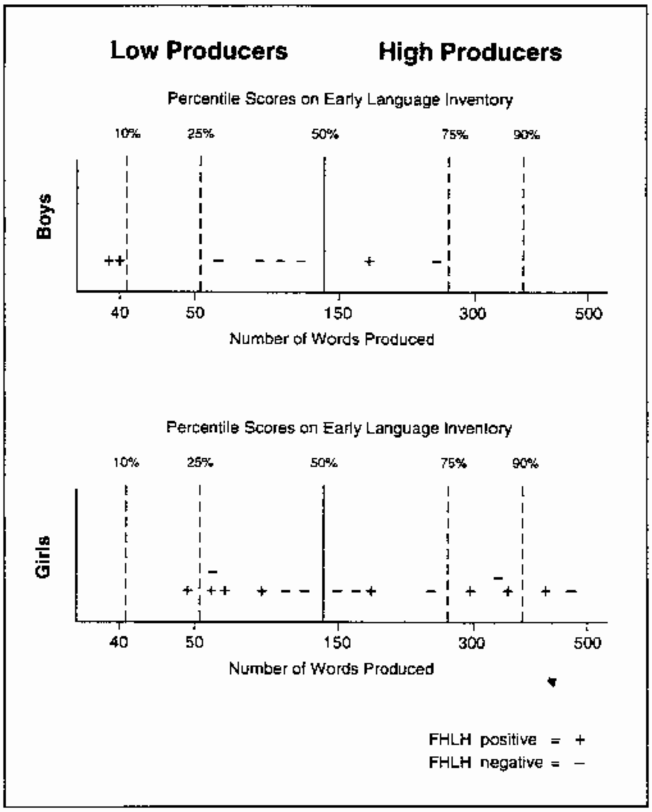


Figure 1. Individual percentile scores and number of words produced on ELI for high and low producers, girls and boys, and children with and without a family history of left handedness (FHLH).

Children with High and Low Productive Vocabularies

The norms from the ELIs were used to separate the children into two groups based on language production abilities. The ELI norms were used instead of conducting a median split for the present sample in an attempt to better reflect true population differences. The distribution of the individual scores and relative percentile ratings on the ELI for children in each of the groups (sex, FHLH, and productive vocabulary) is illustrated in Figure 1. Children who scored above the 50th percentile for 20-month-olds on the ELI were assigned to the "high production" group and children scoring below the 50th percentile on the ELI were assigned to the "low production" group. As can be seen in Figure 1, the "high production" group consisted of nine girls and two boys (five children with and six without a family history of left handedness). The "low production" group consisted of seven girls and six boys (six children with and seven without a family history of left handedness). The means and standard errors for the high and low production groups on each of the behavioral tests are shown in Table 1. As a check for the statistical reliability of the differences between groups on a second measure of productive vocabulary, a one-way ANOVA on the scores from the vocabulary checklist rating scale confirmed that the high and low production groups did indeed differ significantly on this measure of productive vocabulary [$F(1,21)=30.37, p=0.0001$].

The high and low production groups also differed on the measures of language comprehension. Children in the high production group scored significantly better on the comprehension book than did those in the low production group [$F(1,19)=6.62, p=0.018$]. The high production group also tended to score higher on the checklist rating scale for comprehension, however, this effect only approached significance, $p=0.08$.

ERPs

ERPs were averaged separately for words whose meaning was comprehended by the child, words whose meaning the child did not comprehend, and backward words. The data for each ERP component were analyzed separately in mixed-model ANOVAs with repeated measures on two levels of group (high productive vocabulary and low productive vocabulary), three levels of word type (comprehended, unknown, and backward), two levels of hemisphere (left and right), and four levels of electrode site (frontal, temporal, parietal, and occipital). The BMDP 4V program from the BMDP88 package was used to conduct the primary ANOVAs and planned comparisons. The Greenhouse–Geisser Correction for repeated measures was applied to all measures with more than 1 degree of freedom. Tukey's Honestly Significant Difference (HSD) method (Tukey, 1977) was used for post hoc comparisons. The main effects and interactions for the entire sample will be presented first, followed by group effects due to differences in language abilities.

ERP Waveforms

Figures 2 and 3 display the ERPs averaged across all 24 subjects to the words that were comprehended, words that were unknown, and backward words. The different types of words elicited a series of positive and negative deflections that varied in morphology and distribution across the scalp. A positive peak at approximately 100 msec (P100) was elicited to all stimuli, followed by two negative peaks at 200 msec (N200) and 350 msec (N350), that were elicited only to the comprehended and unknown words. Both the N200 and N350 were absent or attenuated to the backward words. Although the N350 to comprehended and unknown words was not clearly defined in the superaverage, this component was apparent in the individual subjects. Attenuation of the N350 in the superaverage can be attributed to individual differences in the latency and amplitude of this component. Subsequently, a broad negative wave with an anterior distribution was evident from 600 to 900 msec (N600–900) to all stimuli.

These components probably relate to the series of positive and negative deflections elicited to auditory stimuli in adults. It is likely that the P100 is equivalent to the auditory P1 (30–100 msec) in adults, which is modulated by changes in the physical parameters of the stimuli (i.e., loudness, duration), and shows little variation in amplitude and latency across subjects who are similar in age (see Hillyard & Picton, 1987; Holcomb, Coffey, & Neville, 1992; Wood & Wolpaw, 1982). The N200 may be equivalent to the N1, or N100 (50–150 msec), which is comprised of a set of multiple contributors and has been shown to be sensitive to both sensory and cognitive factors (Hansen, Dickstein, Berka, & Hillyard, 1983; Picton & Stuss, 1980; Naatanen & Picton, 1986; Regan, 1989). The latency and frontal distribution of the N600–900 is reminiscent of the Nc component elicited only in infants and children (Courchesne, 1983). The Nc displays a frontal distribution and is modulated by stimulus probability (Courchesne et al., 1981; Karrer & Ackles, 1987; Kurtzberg, 1985; Kurtzberg & Vaughn, 1985).

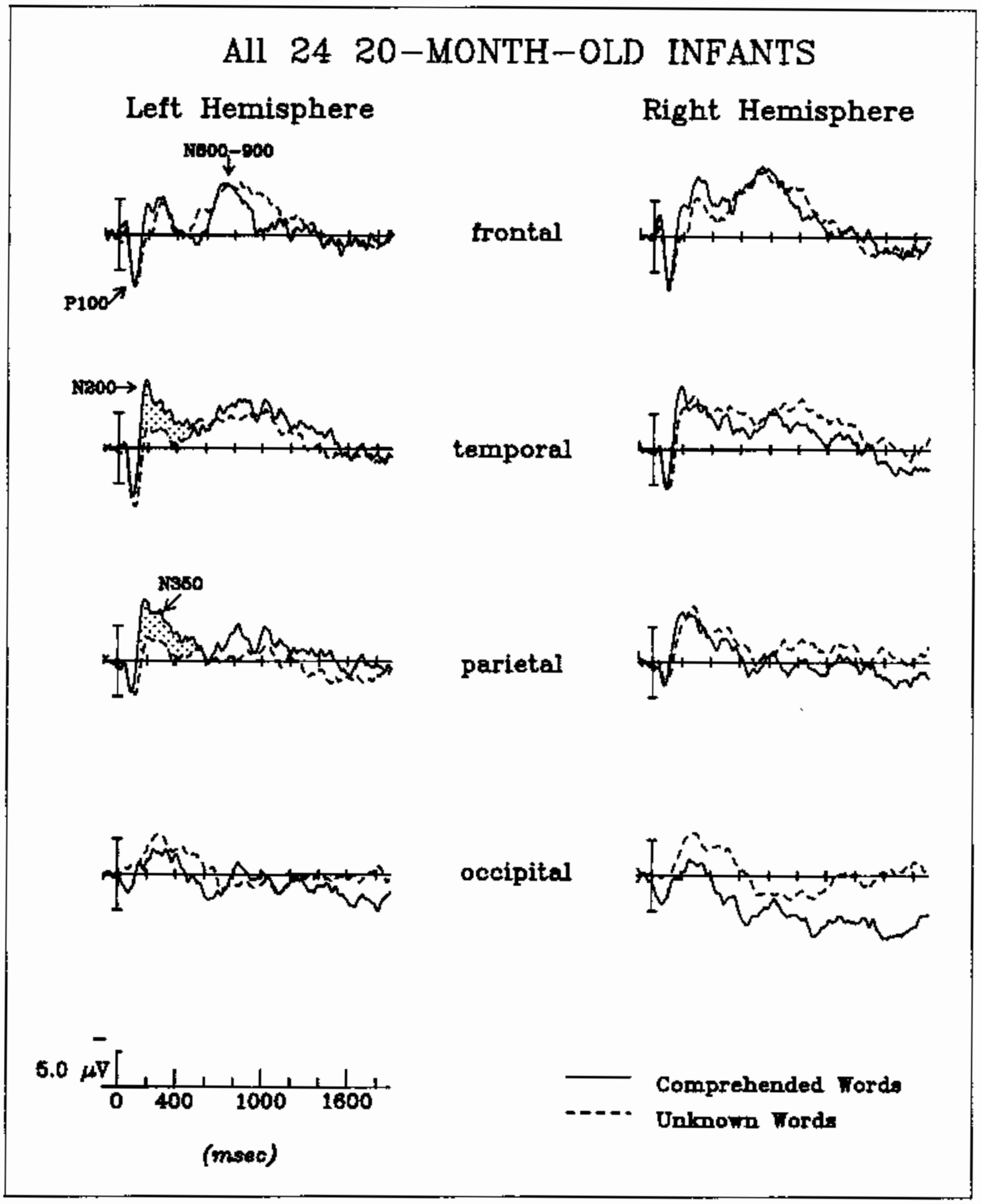
P100

The latency of the P100 did not differ for the different experimental conditions.

For all three types of stimuli the amplitude of the P100 was larger from over anterior than posterior regions [electrode site, $F(3,66)=10.70, p=0.0004$] (Figs. 2 and 3). Additionally, the P100 was larger over the left than the right hemisphere, but only over anterior sites [hemisphere × electrode site, $F(3,66)=13.31, p=0.0001$]. Over occipital areas the asymmetry was reversed, $p=0.01$ [Tukey's HSD].

P100 Sensitivity to Word Type. There were no significant differences in P100 amplitude for the three types of

Figure 2. ERPs to comprehended and unknown words in all normal 20-month-old children over frontal, temporal, parietal, and occipital regions of the left and right hemispheres.



words. However, from visual inspection of the ERPs there appears to be marked amplitude differences between experimental conditions over the occipital sites. A separate ANOVA conducted for the occipital areas alone revealed no significant differences between conditions [$F(2,44)=1.59, p=0.22$].

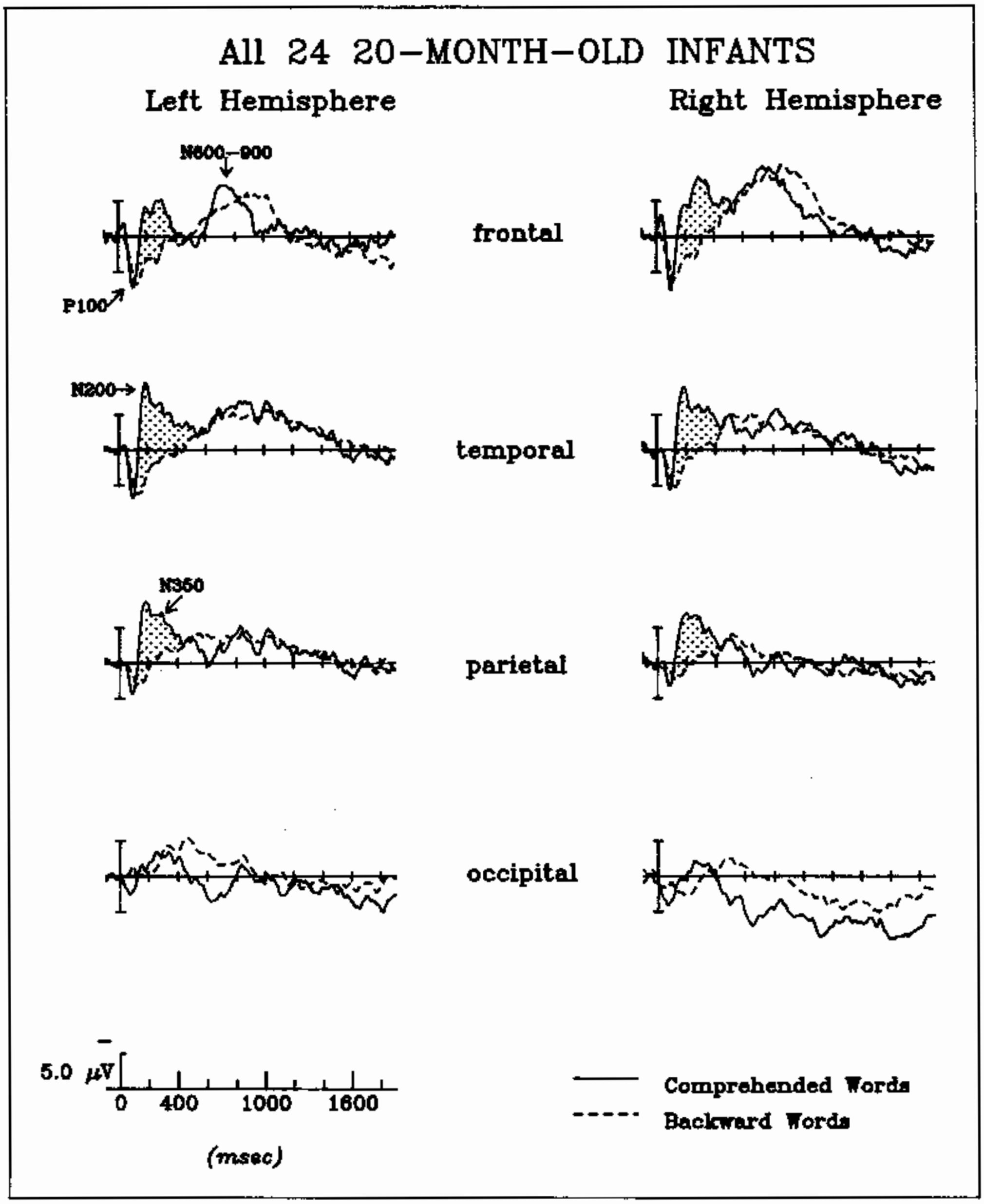
N200

The first negative deflection peaked at around 200 msec (N200). There were no main effects nor interactions for the latency of the N200.

The amplitude of the N200 varied for the different types of words [$F(2,44)=20.65, p=0.0001$] (Fig. 4). Moreover, two-way interactions indicated that the responsiveness of the N200 to the different types of words varied both between and within the two hemispheres [word type × hemisphere, $F(2,44)=4.36$, $p=0.02$, and word type × electrode site, $F(6,132)=3.29$, $p=0.05$]. To examine these interactions, direct comparisons were conducted between word types for comprehended versus unknown words, comprehended versus backward words, and unknown versus backward words.

N200 Sensitivity to Word Type. The N200 to comprehended words was larger than the N200 to unknown words [word type, $F(1,22)=6.57$, $p=0.018$, qualified by two-way interactions, i.e., word type × hemisphere, $F(1,22)=10.47, p=0.004$, and word type × electrode site interaction, $F(3,66)=2.96$, that approached significance, $p=0.06$]. Examination of the interactions revealed that comprehended words were discriminated from unknown words only over temporal and parietal regions of the left hemisphere [comprehended versus unknown

Figure 3. ERPs to comprehended and backward words in all normal 20-month-old children over frontal, temporal, parietal, and occipital regions of the left and right hemispheres.



words at left temporal, $F(1,22)=20.98, p=0.0001$, left parietal, $F(1,22)=21.68$, $p=0.0001$] (see Figs. 2 and 4). Inspection of the data from the individual subjects showed that approximately 90% of the children, i.e., 21 of 24, showed larger N200 amplitudes to comprehended than unknown words over temporal and parietal regions of the left hemisphere. However, 80% of the children, i.e., 19 of 24, displayed the larger N200 to comprehended than unknown words at additional electrode sites (most frequently at left frontal and right temporal and parietal sites). Hence, the statistical analyses indicate this pattern was reliable only across children at the temporal and parietal regions in the left hemisphere, not that most children showed the effect *only* at these sites.

The N200 was larger to comprehended than backward words [$F(1,22)=40.42$, $p=0.0001$] (Figs. 3 and 4). This effect was significant only at sites anterior to the occipital regions, [word type × electrode site, $F(3,66)=5.37$, $p=0.01$].

The N200 was significantly larger to unknown words than to backward words [$F(1,22)=10.19, p=0.001$], qualified by a word type × hemisphere interaction [$F(1,22)=5.29$, $p=0.03$] (Fig. 4). Examination of the interaction revealed that the difference between unknown and backward words was significant only over the right hemisphere [word type at right hemisphere, $F(1,22)=16.64, p=0.0005$].

The significant interactions with word type noted above can also be examined by illustrating the marked differences in the distribution of the N200 to comprehended, unknown, and backward words (see Fig. 4).

For the comprehended words, a significant electrode site effect [$F(3,66)=4.83$, $p=0.01$] revealed that the amplitude of the N200 was larger over temporal and parietal

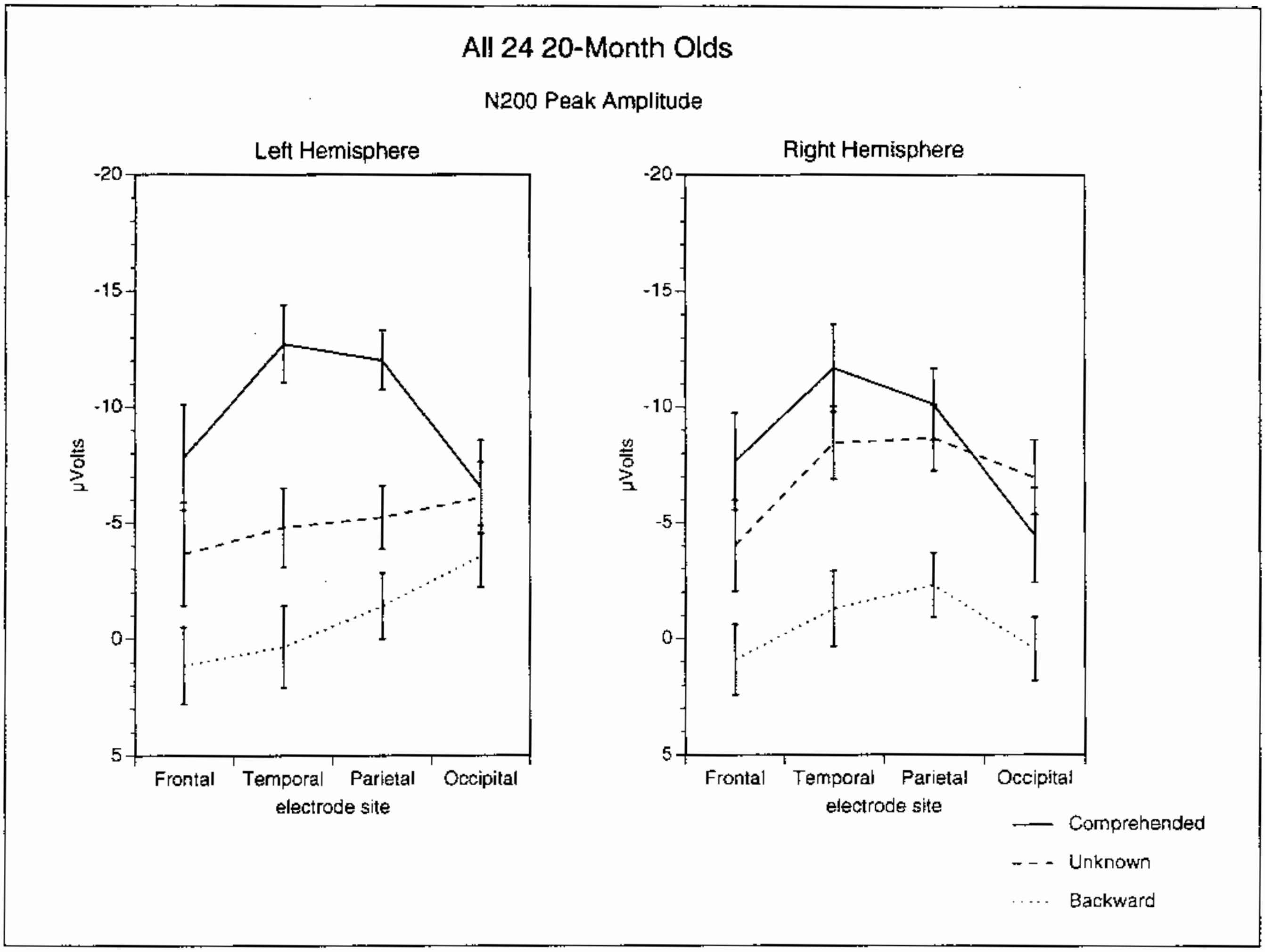


Figure 4. N200 peak amplitudes to comprehended, unknown, and backward words for all normal 20-month-old children.

than frontal and occipital regions (comprehended words, Tukey's for frontal versus temporal, $p<0.05$, and parietal versus occipital, $p<0.05$).

For the unknown words, in contrast to the comprehended words, there were no significant differences in the anterior–posterior distribution of the N200. However there was a robust asymmetry, in that the amplitude of the N200 was larger from the right than the left hemisphere [unknown words, hemisphere $F(1,22)=6.52$, $p=0.018$].

Unlike the N200 to comprehended and unknown words, the ERPs to backward words within this window (125 to 250 msec) were actually more positive over anterior than posterior regions, but only over the left hemisphere [backward words, electrode site, $F(3,66)=7.09$, $p=0.0003$, electrode site × hemisphere, $F(3,66)=7.09$, $p=0.0003$].

N350

A second negative peak occurred around 350 msec (N350). The latency of this peak varied for the different types of words [$F(2,44)=4.00$, 8 $p=0.03$]. The N350 to comprehended words and unknown words peaked earlier than did the N350 to backward words by 22 and 20 msec, respectively. However, the only significant difference was between the comprehended and backward words [$F(1,22)=5.96, p=0.02$].

The amplitude of the N350 also showed differential responsiveness to the different types of words [$F(2,44)=3.17, p<0.05$] (Fig. 5).

N350 Sensitivity to Word Type. The amplitude of the N350 did not differentiate comprehended and unknown words when averaged across all electrode sites. However, like the N200, the N350 was larger to comprehended than unknown words over temporal and parietal regions of the left hemisphere [word type at left temporal, $F(1,22)=4.29$, $p=0.05$, word type at left parietal, $F(1,22)=4.44, p=0.05$]. The N350 was larger to comprehended than backward words, and was larger to unknown words than to backward words over the right hemisphere [word type by hemisphere for comprehended and backward words, $F(1,22)=4.34$, $p=0.05$],

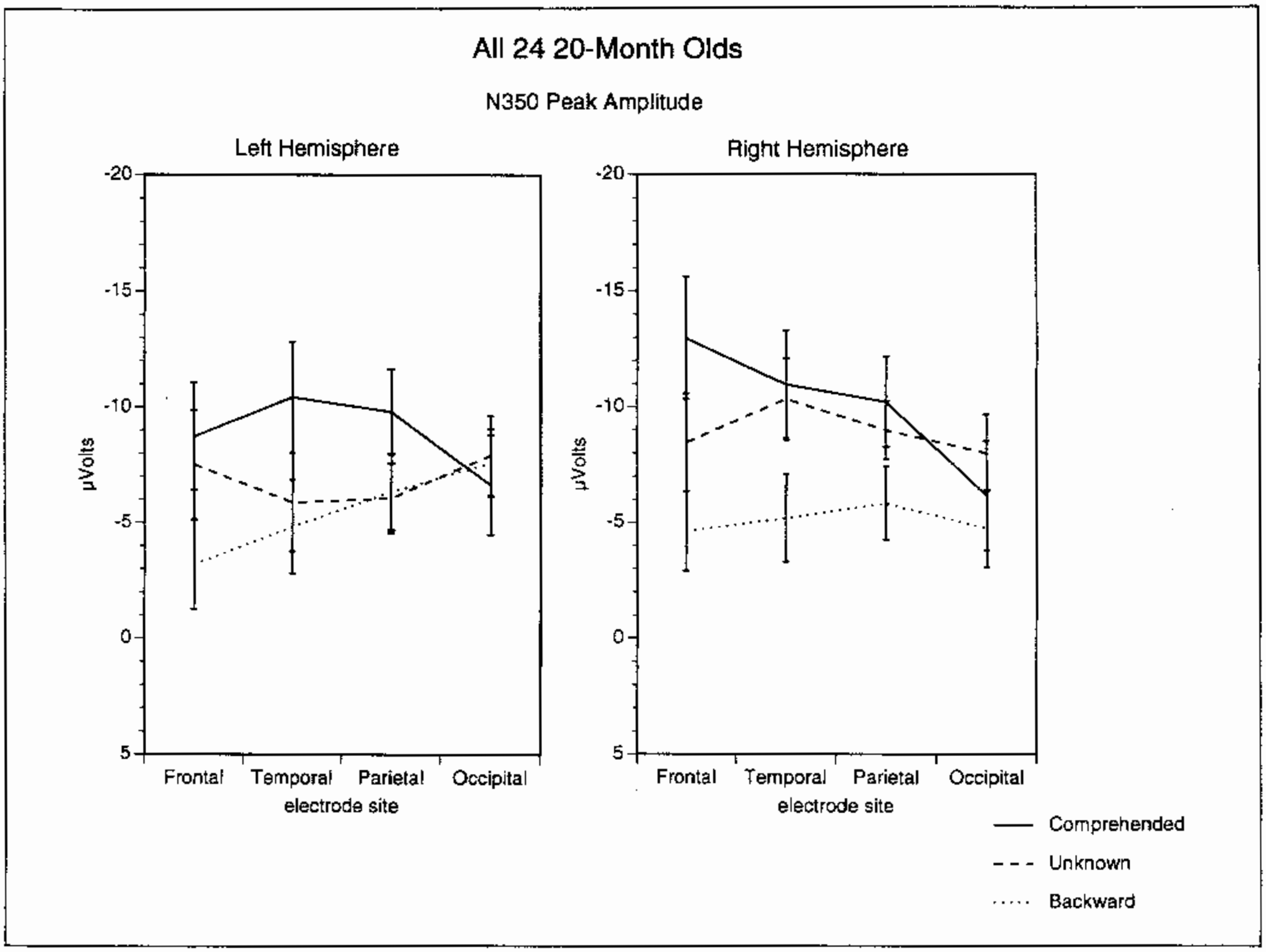


Figure 5. N350 peak amplitudes to comprehended, unknown, and backward words for all normal 20-month-old children.

word type × hemisphere for unknown and backward words, $F(1,22)=6.12, p=0.02$].

Like the N200, the distribution of the N350 varied for the different types of words (Fig. 5). The amplitude of the N350 to comprehended words was bilateral and tended to be larger from anterior than posterior regions, but this effect only approached significance [electrode site, $F(3,66)=2.84, p=0.09$]. For the unknown words, the N350, like the N200, was significantly larger over the right than the left hemisphere [$F(1,22)=14.01, p=0.001$]. And, like the N200, the N350 was absent or attenuated to backward words.

N600–900

For all three types of words there was a broad negative component from 600 to 900 msec that displayed an anterior distribution, and over anterior regions was larger from the right than the left hemisphere [electrode site, $F(3,66)=16.31, p=0.0001$, electrode site by hemisphere, $F(1,22)=5.07, p=0.005$]. There were no significant differences in amplitude or distribution of the N600–900 for the different types of stimuli.

Summary of ERP Sensitivity to Word Type

Both comprehended and unknown words were characterized by two negative peaks at 200 and 350 msec, i.e., N200 and N350, that were absent or attenuated to backward words. Comprehended words were discriminated from unknown words over temporal and parietal regions of the left hemisphere by 200 msec after the onset of the word. That is, the amplitudes of the N200 and N350 were larger to comprehended than unknown words, but the effect was significant only over temporal and parietal regions of the left hemisphere.

Comprehended words were discriminated from backward words by 200 msec after the onset of the word in that the ERPs to comprehended and unknown words were more negative than ERPs to backward words.

ERP Sensitivity to Language Abilities

In this section, the effects of group differences in language production abilities (i.e., high producers versus low producers) on the latency, amplitude, and distribution of ERPs to the different types of words are reported for each of the ERP components.

For all of the following components, there were no group differences for the backward words. Thus the following results are for comparisons of comprehended and unknown words only.

P100 Sensitivity to Language Abilities. There were no significant main effects or interactions with language group for the latency or amplitude of the P100.

N200 Sensitivity to Language Ability. There were no significant main effects or interactions with the latency of the N200 for the two language groups.

There were group differences in the amplitude and distribution of the N200 to comprehended and unknown words. The N200 to comprehended and unknown words was on average 3.5 μV larger for the low producers than the high producers [language group: $F(1,22)= 5.19$, $p=0.03$]. The distribution of the N200 to comprehended words differed for the two groups anterior to the parietal regions (Figs. 6 and 7). For the high production group the amplitude of the N200 was larger over temporal and parietal than frontal regions [high producers: electrode site, $F(2,44)=5.17$, $p=0.02$] (Fig. 6). In contrast, the low production group did not show the same temporoparietal distribution, rather the N200 to comprehended words was not significantly different over frontal, temporal, and parietal regions. Over the occipital areas, both groups showed equally attenuated N200 responses to comprehended words.

The two groups showed the same pattern of responsiveness for the N200 to comprehended and unknown words. That is, like the results from the entire sample, both the high and the low producers displayed significantly larger N200 responses for comprehended than unknown words only over temporal and parietal regions of the left hemisphere [high producers: word type at left temporal, $F(1,10)=9.91$, $p=0.01$, at left parietal, $F(1,10)=34.59$, $p=0.0002$; low producers: word type at left temporal, $F(1,12)=11.83$, $p=0.005$, at left parietal, $F(1,12)=5.81$, $p=0.03$].

N350 Sensitivity to Language Abilities. The latency of the N350 to comprehended words varied with language abilities, i.e., it was significantly earlier for the high than the low production group [$F(1,22)=5.87$, $p=0.02$]. Moreover, for the high production group, this component was well defined and peaked at around 324 msec. For the low production group, the N350 was later (352 msec) than it was for the high production group, and it was more variable across subjects. Because of this latency jitter, the N350 from the low production group appears attenuated and not as well defined as for the high production group (Fig. 7). There were no latency differences between groups in the N350 to unknown words.

In contrast to the results for the N200, the responsiveness of the N350 amplitude to comprehended and unknown words varied with language ability. The N350 amplitude difference between comprehended and unknown words was significant only for the high production group over temporal and parietal regions of the left hemisphere [high producers: word type at left temporal, $F(1,10)=6.30$, $p=0.03$, at left parietal, $F(1,10)=9.35$, $p=0.01$]. For the low production group, there were no significant differences in the amplitude of the N350 between comprehended and unknown words at any electrode site.

N600–900 Sensitivity to Language Abilities. Like the results from the entire sample, the mean area of the N600–900 did not differ for the different types of words at any electrode site for either language group. However, the distribution of the N600–900 to comprehended words differed for the two language groups [language group × word type × hemisphere, $F(1,22)=11.46$, $p=0.003$]. For the high production group the N600–900 was largest over the right frontal region [comprehended words: hemisphere × electrode site, $F(3,30)=4.55$, $p=0.03$]. By contrast, for the low production group the N600–900 displayed a bilateral anterior distribution [comprehended words: electrode site, $F(3,36)=8.05$, $p=0.001$].

Visual inspection of the data suggested that the low producers may have larger amplitude N600–900 responses to comprehended words than did the high producers. Tukey's HSD tests between groups showed that for the comprehended words the amplitude of the N600–900 was larger for the low than the high production group over the temporal, $p<0.01$, and parietal, $p<0.05$, regions of the left hemisphere. Additionally, for the unknown words the N600–900 amplitude was larger for the low than the high producers over the right parietal region, $p<0.05$.

Group Differences for Sex and Family History for Left Handedness

Separate ANOVAs were conducted with sex or family history of left handedness (FHLH) as the grouping factors for each of the components described above. There were no significant main effects or interactions for sex or family history for left handedness for any of the components. Of particular importance, unlike the results reported by Molfese (1990), there were no sex differences in the laterality of ERP responsiveness to comprehended and unknown words. That is, the N200 was larger to comprehended words than unknown words over the temporal and parietal regions of the left hemisphere for

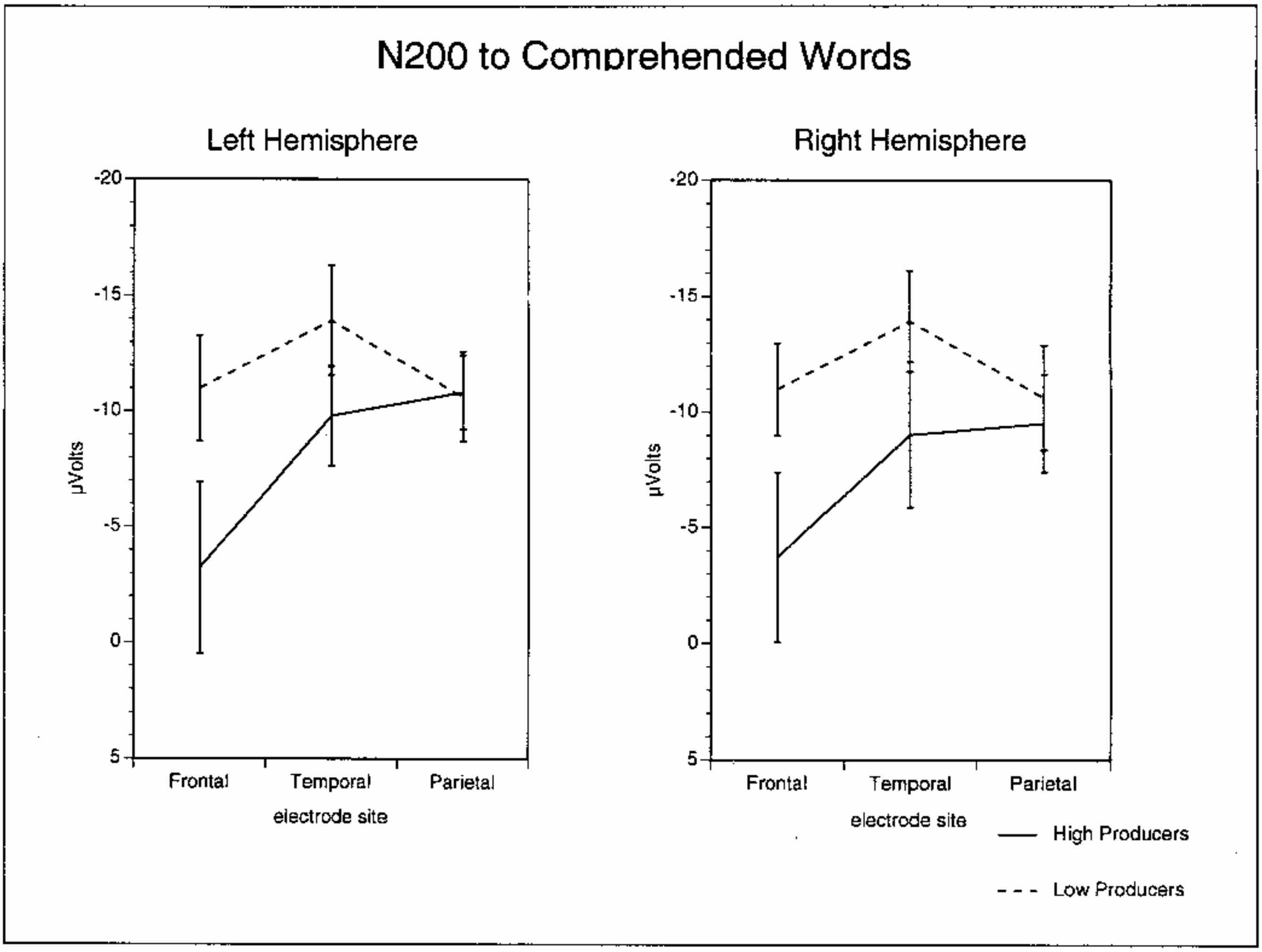


Figure 6. N200 peak amplitudes to comprehended words for 20-month-old high and low producers.

both boys and girls [boys: word type for comprehended and unknown words at left temporal, $F(1,7)=9.34$, $p=0.02$, left parietal $F(1,7)=9.08$, $p=0.02$; and girls: left temporal, $F(1,15)=12.36$, $p=0.003$, left parietal, $F(1,15)=19.91$, $p=0.0005$].

Sex differences were of particular interest in view of previous reports by Molfese (1989) and Schucard et al. (1981), suggesting that ERP laterality effects differed for boys and girls. Because our behavioral data showed that girls tended to produce more words than boys, we explored the possibility that our group differences for language abilities might be confounded with sex differences (and vice versa for Molfese, 1990). To examine this possibility, when significant effects for language abilities were obtained, we conducted separate analyses for sex effects by holding language abilities constant, i.e., eight girls were matched to the eight boys for both language comprehension and production abilities. There were no significant main effects nor interactions with sex when language abilities were held constant.

DISCUSSION

The purpose of the present study was to examine patterns of neural activity relevant to language processing in 20-month-old infants, and to determine what changes in the organization of brain activity occur as a function of changes in language development. The results demonstrate that specific ERP components, i.e., N200 and N350, are associated with language comprehension in 20-month-old children. Moreover, these data are consistent with the hypothesis, raised by previous studies of hearing and congenitally deaf adults (Neville, 1991a,b; Neville et al., 1982a,b, 1992), and bilingual adults (Weber-Fox & Neville, 1992), that level of language competency is positively linked to the degree of specialization of neural systems subserving language processing.

Of particular interest was to examine the neural responses to comprehended and unknown words. ERPs to comprehended and unknown words were different by at least 200 msec after word onset, as indexed by the N200 and N350. Moreover, this pattern of responsiveness was limited to temporal and parietal regions of the left

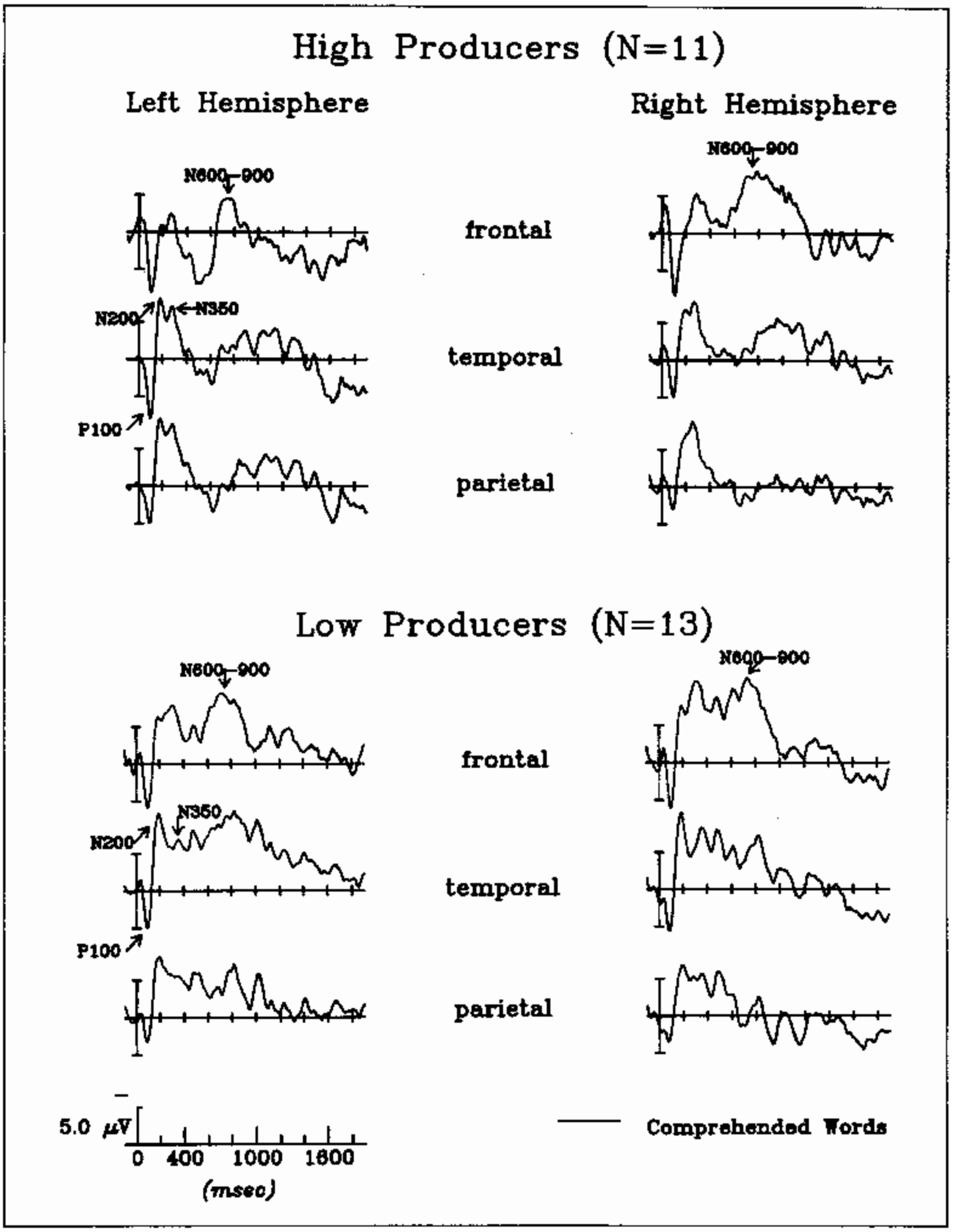


Figure 7. ERPs to comprehended words for 20-month-old high and low producers over frontal, temporal, and parietal regions of the left and right hemispheres.

hemisphere. The results suggest that by at least 20 months of age, specialized brain systems mediate the processing of words that are comprehended by the child, and that these systems are distinct from those activated during the processing of words the child does not understand. These data also raise the hypothesis that there is some degree of left hemisphere specialization for language comprehension in infants as young as 20 months of age.

Differential activation of neural systems subserving comprehended and unknown words was illustrated by the marked differences in the inter- and intrahemispheric distributions of the N200 and N350 to these stimuli. Comprehended words elicited responses that were bilaterally symmetrical and showed a temporoparietal distribution. By contrast, the unknown words elicited asymmetrical N200 and N350 responses that were larger over the right than the left hemisphere, and were equipotential from anterior to posterior regions.

The asymmetrical, right greater than left, N200 and N350 responses to unknown words may reflect right hemisphere involvement in the processing of novel but meaningful stimuli. Goldberg and Costa (1981) proposed that the right hemisphere plays a critical role in the initial stages of acquisition of a variety of cognitive abilities including language, because the neuroanatomical organization of the right hemisphere is better suited to processing novel stimuli, whereas the left hemisphere is superior at utilizing well-routinized codes. They propose a right to left shift in hemispheric specialization as a function of increased competence with respect to a particular type of processing.

In contrast to comprehended and unknown words, backward words did not elicit N200 or N350 responses in either hemisphere. Of particular interest was that the distribution of the difference in the N200 response to comprehended and backward words was bilateral and widely distributed over anterior and posterior regions. This pattern was in contrast to the asymmetrical left temporoparietal distribution of the N200 responsiveness to comprehended and unknown words. The data from the backward words provided an important control because they suggest that the distribution of the N200 difference to comprehended and unknown words is specific to differences in word meaning, and not simply to the differentiation of words from just any complex auditory stimuli. Moreover, differences in the distribution of the N200 responsiveness to the different types of words lend further support to the hypothesis that nonidentical neural systems mediate processing of comprehended, unknown, and backward words.

The second goal of the present study was to examine changes in the organization of language-relevant neural systems linked to differences in language production abilities. Significant group differences related to level of language abilities were observed for the amplitude and distribution of the N200 and N600–900, and for the latency and responsiveness of the N350 for comprehended and unknown words.

When group differences in overall amplitude or latency of ERPs were observed, the high production group elicited ERPs that were smaller and earlier than did the low production group. That is, the amplitude of the N200 and N600–900 to comprehended and unknown words were smaller for the high than the low producers, and the latency of the N350 to comprehended words was earlier for the high than the low producers.

When group differences in the *distribution* of ERPs were observed, the high producers displayed more focally distributed responses than did the low producers for both the N200 and N600–900 to comprehended words. The N200, which was linked to language comprehension, displayed neural activity that was focally distributed over temporal and parietal regions for the high producers, but was more widely distributed over anterior and posterior regions for the low producers. Similarly, the distribution of the N600–900 was limited to frontal regions in the high than the low producers and was more widely distributed in the low producers. However, the functional significance of this response is not known. As suggested earlier the N600–900 may be related to the Nc, which is sensitive to stimulus probability. The N600–900 did not differ for the three types of words, possibly because the different types of stimuli were presented with equal probability. It has been suggested that the Nc is linked with attentional processes (Courchesne, 1983). (Posner and Rothbart, 1991; Rothbart, Posner, & Boylan, 1990) proposed an anterior attention system in infants that is generated in the anterior cingulate. They suggest that this system may be linked with the integration of sensory, emotional, and language stimuli. It will be important to further investigate the role of attentional mechanisms in language abilities in future research. In summary, these data raise the hypothesis that group differences in the distribution of the N200 and N600–900 to comprehended words reflect differences in the specialization of neural activity linked to language processing, i.e., the high producers show a more specialized pattern of responses.

Several factors could have accounted for the group differences observed in ERPs. First, the majority of the high producers were girls, therefore group differences could have been confounded with sex differences, which have been demonstrated elsewhere (e.g., Molfese, 1990 for 16-month-olds; Shucard et al., 1981 for 3-month-olds). However, in the present study there were no reliable sex effects or interactions with sex for the sample as a whole or when language abilities were held constant. Thus, it is unlikely that sex differences could have accounted for the group differences for level of language ability in the present study.

Second, group differences in ERPs could reflect general maturational differences between the two groups. Changes in ERPs that occur with increasing age typically show decreases in the latency and amplitude of ERP components (Courchesne, 1978; Holcomb et al., 1992; Johnson, 1989). These age-related changes are observed for both early and late components in response to a variety of different stimuli, and are likely to be associated with widely distributed changes in brain development, i.e., increased myelination, loss of synapses, dendritic branching (Huttenlocher, 1979; Huttenlocher, Courten, Garey, & Van Der Loos, 1982; Conel, 1963). If general maturational factors are responsible for group differences in ERPs, amplitude and latency differences between groups should be apparent in ERP components to all types of stimuli. However, the results showed that group differences in ERPs were limited to the N200 and N600–900 to comprehended and unknown words, i.e., there were no group differences for backward words. Moreover, there were no amplitude or latency differences between the high and low producers for the P100, which have been shown to significantly decrease with age (Holcomb et al., 1992). The only significant latency difference was limited to the N350 to comprehended words. If group differences were due to overall rates of brain maturation, a large number of latency differences would be expected, and latency and amplitude differences would be observed for all three types of words.

Of particular interest here were the group differences in the distribution of the N200 and N600–900 to comprehended words. Age-related changes in the distribution of ERPs to auditory words have also been reported (Holcomb et al., 1992). However, because children at different ages also vary in language abilities it is not possible to determine which factors may have been due to maturation and which to level of language competence.

Another explanation for group differences in the distribution of the N200 and N600–900 is that increased specialization of neural systems subserving language may be linked to increasing language abilities. The hypothesis that more focal, i.e., more specialized, neural responses are associated with higher levels of language abilities has been suggested in studies of adults using a variety of techniques, including electrical stimulation mapping in monolingual (Ojemann, 1991) and bilingual patients (Cawthon, Ojemann, & Lettich, 1991), a combination of intracarotid amobarbital, electrical stimulation, and positron emission tomography in a study of a bilingual patient (Fedio et al., 1992), and ERPs with healthy bilinguals (Weber-Fox & Neville, 1991, 1992) and deaf and hearing adults (Neville, Mills, & Lawson, 1992). Thus, it is our working hypothesis that general differences across conditions and ERP components are linked to general maturational differences, whereas differences in the organization of language-relevant ERP responses are linked to level of language abilities.

In summary, the results suggest that by 20 months of age distinct neural systems mediate processing of comprehended, unknown, and backward words. Moreover, the organization of the neural activity mediating language comprehension is linked to level of language production abilities.

The results from the present study appear to differ from those of Molfese, who reported that comprehended and unknown words elicit different ERPs in 14-month-olds (Molfese, 1989) and 16-month-olds (Molfese, 1990). Molfese used a Principle Component Analysis (PCA) technique and characterized the data in terms of principal components rather than describing the morphology of the ERP waveforms as a series of positive and negative peaks. Therefore, it was difficult to directly compare the results from the present study with the studies by Molfese because of differences in data analysis and presentation. For a review of potential problems with the PCA method see Wood and McCarthy (1984).

Most marked were differences between the present study and the Molfese studies in the latencies, distributions, and polarity of the ERP differences between comprehended and unknown words. In contrast to the present study, which showed ERP responsiveness to comprehended and unknown words at 200 and 350 msec, Molfese reported principal components that discriminated known from unknown words with mean latencies of 170, 320, and 440 msec for 14-month-olds (Molfese, 1989), and 270 and 650 msec for 16-month-olds (Molfese, 1990). Additionally, Molfese reported larger negative responses to unknown than known words, i.e., the polarity of the difference between comprehended and unknown words was reversed from that found in the present study.

A variety of methodological differences between the present study and the studies by Molfese might have contributed to the differences in the data: (1) The data reported by Molfese were recorded from younger children than in the present study. However, our ERP data from younger children 13–17 months of age using the same paradigm (Mills, Coffey, & Neville, 1991, 1992, 1993) display similar results, i.e., similar in latency and polarity of differences to comprehended and unknown words to those reported in the present study. (2) Another difference was that Molfese presented each child with only two different words, one the child appeared to comprehend and one the child did not appear to know. Studies of semantic satiation have shown that when words are repeated many times in succession they tend to lose meaningfulness, and this effect has marked effects on ERPs (Rugg, 1986, 1990; Kounios & Holcomb, 1990). (3) The two studies differed in the type of "unknown" words used. Molfese selected both known and unknown words from a set of 10 words children in the 14–16 month age range would be likely to comprehend. By contrast, in the present study the unknown words were chosen from a separate set of words children in this age range would not be likely to know. Thus, the "unknown" words in the two studies probably vary in their familiarity to the subjects. (4) Molfese did not report the use of an electrode below the eye for purposes of artifact rejection. Using a set amplitude criterion based on cortical sites alone for artifact rejection is problematic and can adversely affect the signal-to-noise ratio. It will be important to replicate these studies and further explore these issues using a variety of paradigms to resolve the differences in the findings between different researchers.

CONCLUSION

The results suggested that by 20 months of age there is a considerable degree of cerebral specialization for language processing both within and between the two hemispheres. Lateral specialization was demonstrated in the N200 and N350 responsiveness to comprehended and unknown words. Anterior–posterior specialization was demonstrated by (1) different patterns of N200 and N350 responsiveness to the different types of words over frontal, temporal, parietal, and occipital regions, of both hemispheres, and (2) differential distributions of the N200 and N600–900 to comprehended words as a function of language abilities.

If we adopt the working hypothesis, suggested by the results, that the amplitude of N200 and N350 index the degree to which brain systems specialized for processing meaningful language information are activated, then the following proposals are suggested. By 200 msec after word onset, words that are comprehended and produced activate specific systems, indexed by the N200, within both the left and the right hemispheres. Unknown words activate systems largely within the right hemisphere either because the left hemisphere N200 and N350 have been suppressed or have not developed. Further research at different ages will clarify this issue. Backward words do not elicit activity within these systems in either hemisphere. In the present study, the asymmetry in response to comprehended versus unknown words arises from the asymmetrical response to unknown but potentially meaningful words. Thus, at this point in development the mature pattern of ERPs, including a left greater than right response to comprehended words, is not evident. Results from ongoing studies of older children, both with single words and sentences chart the course of this development (Holcomb, Coffey, & Neville, 1992; Neville, 1991a,b). Additionally, the results are consistent with the hypothesis that the functional organization of language-relevant brain systems becomes progressively more specialized with increasing language abilities. An important direction for future research is to explore whether specific changes in the cerebral organization for language precede, accompany, or follow the attainment of different language milestones. More generally, these results suggest that this type of combined behavioral–electrophysiological approach will contribute significantly to the study of the neurobiology of language acquisition in both normal and abnormal development.

METHOD

Subjects

Children were recruited for the study through advertisements in local newspapers, posters displayed in the area, requests at play groups, and referrals from parents whose children had participated in previous studies. Only full-term healthy infants with monolingual experience with English participated in the study.

Thirty-four children 19.5 to 21.75 months of age participated in the study (mean = 20.5 months). Data from 16 girls and 8 boys were retained for analysis. Data from an additional 10 children (4 girls and 6 boys) were not used because the children either refused to keep the Electrocap on for the duration of the session or there was too much eye and/or body movement artifact in the data, i.e., there were fewer than 10 artifact-free trials per condition.

Because hand preference and family history of hand preference have been linked with differential brain organization in adults, we collected information on handedness of the participants and members of their immediate family. Parents were asked to rate their children's hand preference as "right-handed, left-handed, or no hand preference." Based on these parental reports, 20 children showed a preference for the right hand, one showed a left-hand preference, and three of the children did not show any hand preference. Eleven of the children had members of the immediate family (parents and/or siblings) who were left-handed. The one child who showed a left-hand preference and two of the three children who did not show any hand preference had immediate members of the family who were left-handed.

Language Assessment

Within 1 week prior to participating in the electrophysiological portion of the study each child was seen for language testing. The behavioral session was used both to estimate the child's general level of speech and language abilities and to determine which words to present during the electrophysiological testing session. All behavioral sessions were videotaped.

Early Language Inventories (ELI)

The ELI provided parental estimates of language production for single words and early word combinations. The inventory has been normed on over 1000 children from 6 to 30 months of age, and its reliability and validity have been well established for use with children in this age range (e.g., Bates, et al., 1988; Bretherton et al., 1983; Fenson, Flynne, Vella, Omens, Burgess, & Hartung, 1989).

Vocabulary Checklist Rating Scales

Parents were asked to give confidence ratings for 120 words, the majority of which were rated, on the ELI, as frequently comprehended by children in this age range. Parents rated each word on a scale of 1 to 4 for how sure they were that their child did or did not comprehend and/or produce each word. Separate ratings were given for comprehension and production.

Comprehension Book

This task was a simple two-way forced-choice picture–word matching test that consisted of 50 object names, and 9 verbs and modifiers. For each item the child was asked to point to one of two pictures (colored line drawings) that matched the word spoken by the experimenter.[1] This comprehension measure has been validated against the data from the normed language inventories (Bates, Thal, Witesell, Fenson, & Oakes, 1989; Thal & Bates, 1988a,b).

Stimuli

The stimuli were selected from 120 words (from the Vocabulary Checklist Rating Scale) naturally spoken by a female voice. The words had been digitized at 16 kHz and stored on an IBM PC computer. Each word had been edited for precise time of onset to allow for synchronization with the digitization of the ERPs. These words were used to construct a stimulus list for each child prior to ERP testing. When possible we used a standard list across children. Three types of words were used: words the child both comprehended and produced ("comprehended words"), words the child did not comprehend or produce ("unknown words"), and "backward words" (i.e., the comprehended and produced words presented backward). The comprehended and produced words were selected from the words (1) the child correctly identified in the behavioral testing session and (2) received the highest parental rating ("4"—very sure) for both comprehension and production on the vocabulary checklist rating scales. Examples of commonly used words were nose, ball, dog, cat, bear. The unknown words were words rated as "1," i.e., the parents were confident that their child did *not* understand or produce the words. To ensure that the unknown words were not comprehended by the child, the unknown words were selected from a list of low probability words, e.g., pint, tone, fade, staff. Every effort was made to match the comprehended words and the unknown words on word length (duration in ms) and number of syllables. The backward words consisted of the same list of words as the comprehended words except the digitized files were played backward. An editing program was used to ensure that the onset and offset time was the same for forward and backward words. The backward words were used as control responses to complex auditory stimuli with some of the same physical characteristics of speech. The words varied in length from 562.5 to 687.5 msec (mean comprehended and backward = 598.75; mean unknown = 597.5 msec) and were presented at intensities that ranged from 61 to 71 dB (mean comprehended and backward = 66.9; mean unknown = 66.6).

Electrophysiological Testing

Electrode Placement

The EEG was recorded using tin electrodes (Electro-Cap International) from sites over frontal (F7 and F8), temporal (33% of the distance from T3/4 to C3/4 respectively), parietal (50% of the distance between T3/4 and P3/4 respectively), and occipital (O1 and O2) regions of the left and right hemispheres. Additionally, the electrooculogram was recorded from electrodes placed over (Fp1) and under the eye to reject trials on which blinks and vertical eye movement occurred, and from left and right frontal electrodes to reject trials on which horizontal eye movement occurred. All electrodes were referenced to linked mastoids.[2] The EEG was amplified by Grass model 7P511 amplifiers with a bandpass of 0.1 to 100 Hz and sampled every 8 msec for 2 sec following the onset of each word. All electrophysiological sessions were videotaped.

Artifact Rejection

Visual inspection of the data for eye and muscle artifact was conducted off-line on a trial by trial basis. Assessment of responses from electrodes both over and under the eye allows for the discrimination of potentials generated by the eye (which are opposite in polarity above and below the eye) from events generated by the brain (which are the same in polarity). It is our experience that this distinction is critical for obtaining artifact free data, especially in infants and toddlers. The percentage of trials rejected due to eye and movement artifact ranged from 11 to 61% with a mean of 40%. There were no significant differences in the percentage of trials rejected for the different experimental conditions, different language groups, or for girls versus boys.

Testing

Ten of each type: comprehended, unknown, and backward words were used. Each word was presented six times, for a total of 180 trials. Because both eye and muscle movement create artifact in the EEG, it was difficult to obtain artifact-free data from children in this age range. A considerable amount of time and effort was spent developing a procedure that would maintain the children's interest (i.e., keep them sitting still) long enough for us to collect enough usable data. During testing the children sat on their parent's lap and listened to words. The words were presented from a speaker located behind a moving puppet in a puppet theater.[3] The procedure was designed to give the appearance that the puppet was "talking." However, the movements were not synchronized to the word presentations. To maintain the children's interest, a variety of puppets was used. Also, a reinforcement procedure was adopted. After the child sat still and watched the puppet for approximately 10 trials, the experimenter activated a battery-operated toy attached to the front of the puppet theater and praised the child. Development of the procedure made a dramatic improvement in the attainment of artifact-free data.

Measurement of ERP Components

ERP component amplitudes were quantified by computer with reference to the 100 msec prestimulus baseline. Peak amplitudes and latencies (for the maximum negative or positive point in a specified time window) were measured according to the following criteria: N50 was defined as the most negative deflection between 8 and 100 msec, P100 as the most positive deflection between 50 and 175 msec; N200 as the most negative deflection between 125 and 250 msec; and N350 as the most negative deflection between 275 and 450 msec. Additionally the N600–900 was defined and measured as the mean negative amplitude between 600 and 900 msec.

Acknowledgments

We thank Dr. Elizabeth Bates for her comments on an earlier version of this report. This research was supported by Grants DC 00128, DC 00481, and NS 22343 from the National Institute of Health, National Deafness and Other Communication Disorders, and National Institute of Neurological Disorders and Stroke.

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Notes

1. Three children, one girl and two boys, refused to point to pictures. For these children identification of three-dimensional objects was used in conjunction with the rating scale to determine which words to use as "comprehended" words in the ERP testing session.
2. We are aware of controversies pertaining to the use of linked mastoids. We used this procedure to be consistent with our previous work and because we have conducted independent studies that show that the mastoids are inactive and ERP asymmetries are not attenuated by linked references in this task.
3. To test for possible effects of the moving puppet on the ERPs to words we compared the data from the present sample to that from eight children who heard the words presented through a speaker but did not see the moving puppet. The analyses showed that the morphology and latency of the components and their responsiveness to the different types of stimuli did not differ as a function of the presence of the puppet theater.

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